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Analysis of Polarization Mismatch Loss for Horizontal Linear Feature Detection

Mark A. Govoni, *Senior Member, IEEE,* Jeffrey S. Spak, Lee R. Moyer, *Senior Member, IEEE*

***Abstract*—This research investigates the losses incurred by polarization mismatch, and the impact it has on the detection of horizontal linear features for targets in the ground-plane. We introduce a sequence of steps necessary in mathematically determining the percentage of the horizontal linear feature that is co-polarized with the radar slant plane. Using computer simulation, we numerically evaluate and plot the mismatch loss as a function of polarization and grazing/aspect angles.**

***Index Terms*—airborne radar, polarization mismatch loss, horizontal linear feature detection**

I. Introduction

FOR most airborne radar, target detection is possible when the receiver collects target energy in excess of ground clutter and channel noise. Ground clutter is the predominant impediment to successful detection, and is minimized by varying the grazing angle. Extensive literature exists on backscattering statistics for various terrain types [1, 2]. However, little research exists on the significance of aspect angle and its relationship to polarization mismatch loss. Research has been conducted investigating linear feature detection in synthetic aperture radar imagery [3-12]. Furthermore, general research exploring the phenomena encountered by communications systems when varying polarizations has also been conducted [13-18].

Polarization mismatch loss occurs because most imaging geometries have limited aspect to target. This causes the antenna's slant plane to align poorly with the target linear feature, and results in a portion of the transmit signal reflecting at an orthogonal polarization. The polarization mismatch loss is in addition to the (two-way) antenna loss that occurs at target angles off the antenna boresight. By analyzing the polarization mismatch as a function of both aspect and grazing angles, we can numerically evaluate the expected loss as they relate to horizontal linear feature detection.

In Section II, we establish the basis for our vector model and define the vectors used in the subsequent sections. In Section III, we focus on the polarization mismatch resulting when target horizontal linear feature(s) are poorly aligned with the radar line-of-sight vector and derive the polarization mismatch equations as a function of the slant-plane normal and linear feature vector. We then numerically evaluate the expected loss and plot the results. In Section IV, conclusions are made and future efforts are mentioned.

II. Vector Model

We first introduce some assumptions about the target. (1) We assume the target lies on an ideal ground-plane free of surface irregularities. (2) We assume the target surface is symmetric about its central axis and that linear features are much greater than the radar wavelength. In this analysis, we use a North, East, Down (NED) coordinate system where the antenna is located at the origin (0, 0, 0). In our model, the target is located at a point in the ground plane (u_x, u_y, u_h). Therefore, the radar line-of-sight (LOS) vector can be represented by $\mathbf{u}_{\mathrm{LOS}} = [u_x, u_y, u_h]$ and similarly, $\mathbf{u}_{\mathrm{F\_H}} = [-\sin\psi_a, \cos\psi_a, 0]$ represents the horizontal linear feature where ψ_a is the aspect angle. The horizontally-polarized antenna vector is represented by $\mathbf{u}_{\mathrm{A\_H}} = [0, 1, 0]$ and its vertical counterpart is $\mathbf{u}_{\mathrm{A\_V}} = [\sin\theta, 0, \cos\theta]$ where θ is the antenna tilt angle.

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14. ABSTRACT
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15. SUBJECT TERMS
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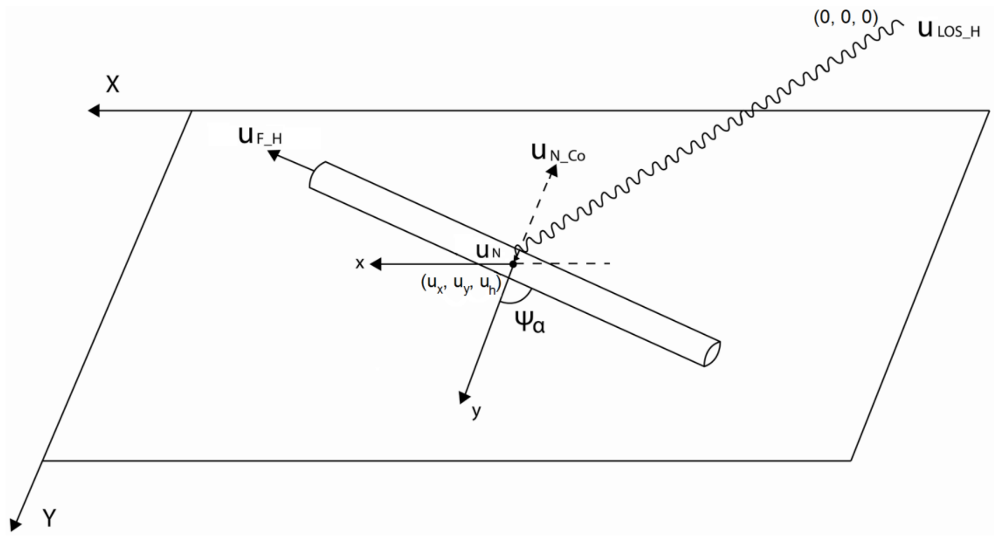
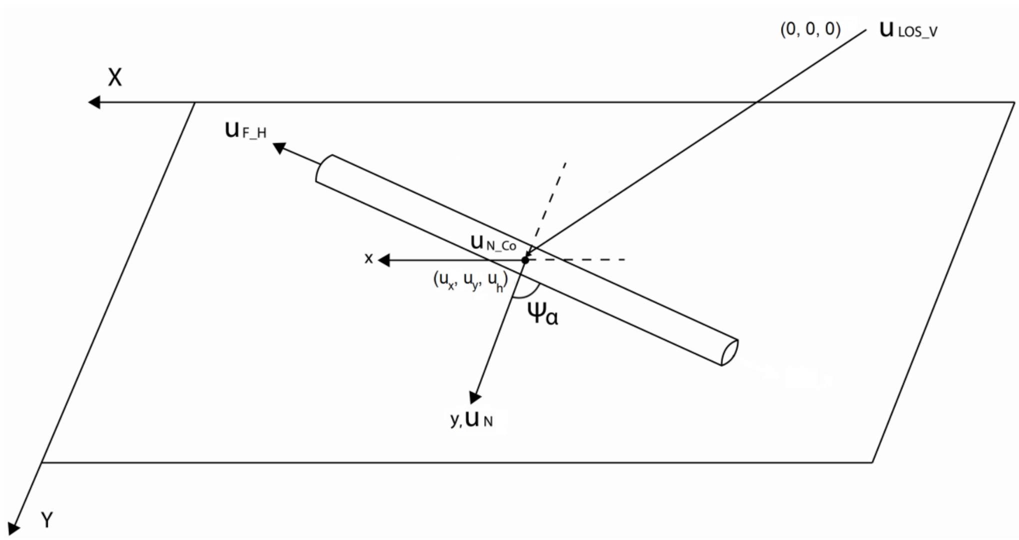
The following describes the basic components of the vector model:

- ψ_g is the grazing angle for the radar LOS vector
- ψ_a is the aspect angle for the radar LOS to the target where 0-deg aspect is considered broadside
- x is the ground-plane projection for the radar LOS vector
- y is orthogonal to x and serves as reference for aspect angle



(a)



(b)

Figure 1. Target geometry relative to radar aspect angle (ψ_a): (a) horizontally-polarized line-of-sight vector ($\mathbf{u}_{LOS\_H}$), (b) vertically-polarized line-of-sight vector ($\mathbf{u}_{LOS\_V}$). Both are projected into the ground-plane bounded by the XY-axes. The horizontal linear feature vector ($\mathbf{u}_{F\_H}$), the slant plane normal ($\mathbf{u}_N$), and the co-polarization vector ($\mathbf{u}_{N\_Co}$) are included.

III. POLARIZATION MISMATCH LOSS

A. Horizontally-polarized slant plane

The horizontally-polarized component of the target linear feature is determined in the following manner:

1. The cross-product of $\mathbf{u}_{A\_H}$ and $\mathbf{u}_{LOS}$ is taken to form $\mathbf{u}_N$, which is orthogonal to the horizontally-polarized slant plane and is formed at the center of the target
2. The cross-product of $\mathbf{u}_{LOS}$ and $\mathbf{u}_N$ is taken to form $\mathbf{u}_{N\_Co}$, which is orthogonal to both vectors
3. The dot-product of $\mathbf{u}_{N\_Co}$ and $\mathbf{u}_{F\_H}$ quantifies the amount of radar return from the linear feature that is contained in the horizontally-polarized slant plane

The unit vector ($\hat{\mathbf{u}}$) orthogonal to the horizontally-polarized slant plane is derived from the cross-product of the horizontally-polarized antenna vector and the radar LOS vector,

$$\hat{\mathbf{u}}_N = \mathbf{u}_{A\_H} \times \mathbf{u}_{LOS} / \|\mathbf{u}_{A\_H} \times \mathbf{u}_{LOS}\|, \tag{1}$$

where $\| \bullet \|$ represents the vector norm. The cross-product is first calculated as

$$\hat{\mathbf{u}}_N = \begin{vmatrix} i & j & k \\ u_{A\_H}(1) & u_{A\_H}(2) & u_{A\_H}(3) \\ u_{LOS}(1) & u_{LOS}(2) & u_{LOS}(3) \end{vmatrix},$$

$$= \begin{vmatrix} i & j & k \\ 0 & 1 & 0 \\ u_x & u_y & u_h \end{vmatrix},$$

$$= \det\begin{vmatrix} 1 & 0 \\ u_y & u_h \end{vmatrix} i + \det\begin{vmatrix} 0 & 0 \\ u_h & u_x \end{vmatrix} j + \det\begin{vmatrix} 0 & 1 \\ u_x & u_y \end{vmatrix} k, \tag{2}$$

where the $\det| \bullet |$ is the determinant. The unit vector can then be represented as

$$\hat{\mathbf{u}}_N = (u_h\, i - u_x\, k) / (u_x^2 + u_h^2)^{1/2}. \tag{3}$$

The cross-product of $\mathbf{u}_{LOS}$ and $\mathbf{u}_N$ produces the co-polarization unit vector,

$$\hat{\mathbf{u}}_{N\_Co} = \mathbf{u}_{LOS} \times \hat{\mathbf{u}}_N = (-u_x u_y\, i + (u_x^2 + u_h^2)\, j - u_h u_y\, k) / [(u_x u_y)^2 + (u_x^2 + u_h^2)^2 + (u_h u_y))^2]^{1/2},$$

$$= (-u_x^2 \tan\psi_a\, i + (u_x^2 + u_h^2)\, j - u_h u_x \tan\psi_a\, k) / [(u_x^2 \tan\psi_a)^2 + (u_x^2 + u_h^2)^2 + (u_h u_x \tan\psi_a))^2]^{1/2}. \tag{4}$$

Thus, if the dot-product of $\mathbf{u}_{N\_Co}$ and $\mathbf{u}_{F\_H}$ is one then the return from the linear feature will be entirely contained within the horizontally-polarized slant plane. This case results when $\psi_a = 0$ degrees. Conversely, if the dot-product is zero then none of the return will be contained within the horizontally-polarized slant plane. This is illustrated in Figure 1(a) where the vector orthogonal to the horizontally-polarized slant plane is shown coming out of the page, while an arbitrary aspect angle adds perspective to the model. As evidenced, the cross-product between the radar LOS vector and the orthogonal vector results in a co-polarization vector that is orthogonal to the radar LOS vector.

To verify this, the dot-product magnitude of the co-polarization and linear feature unit vectors is calculated as,

$$N_{Co\_H} = |\hat{\mathbf{u}}_{N\_Co} \bullet \hat{\mathbf{u}}_{F\_H}|,$$

$$= |(u_x^2 \sin\psi_a \tan\psi_a + (u_x^2 + u_h^2) \cos\psi_a) / [(u_x^2 \tan\psi_a)^2 + (u_x^2 + u_h^2)^2 + (u_h u_x \tan\psi_a)^2]^{1/2}|,$$

$$= |[(u_x^2 / \cos\psi_a) + u_h^2 \cos\psi_a] / [(u_x^2 \tan\psi_a)^2 + (u_x^2 + u_h^2)^2 + (u_h u_x \tan\psi_a))^2]^{1/2}|,$$

$$= |[u_x^2 + u_h^2 (\cos\psi_a)^2] / [u_x^4 + (2u_x^2 u_h^2)(\cos\psi_a)^2 + u_h^4 (\cos\psi_a)^2 + u_h^2 u_x^2 (\sin\psi_a)^2]^{1/2}|,$$

$$= |[u_x^2 + u_h^2 (\cos\psi_a)^2] / [u_x^4 + u_x^2 u_h^2 (1 + (\cos\psi_a)^2) + u_h^4 (\cos\psi_a)^2]^{1/2}|,$$

$$= |[1 + (u_h / u_x)^2 (\cos\psi_a)^2] / [1 + (u_h / u_x)^2 (1 + (\cos\psi_a)^2) + (u_h / u_x)^4 (\cos\psi_a)^2]^{1/2}|. \quad (5)$$

Sample calculations verified that $(N_{X\_H})^2 + (N_{Co\_H})^2 = 1$ where $N_{X\_H} = |\hat{\mathbf{u}}_N \bullet \hat{\mathbf{u}}_{F\_H}| = |-\sin\psi_a / [(1 + u_x / u_h)^2]^{1/2}|$. From here, the polarization mismatch loss in the horizontal plane is calculated as,

$$L_H = 10 \log_{10} (N_{Co\_H})^2. \quad (6)$$

Figure 2 plots the polarization mismatch loss for horizontal polarization when various aspect and grazing angles are considered. In our analysis, the altitude was held constant at 25,000 ft (7.6 km). It can be seen from the figure that the loss increases proportional with increases in both aspect and grazing angles. Therefore, if one wanted to minimize the polarization mismatch loss for a horizontally-polarized radar slant plane, they would need small aspect angles and shallow grazing angles. However, it's important to keep in mind that certain radar applications, such as foliage penetration, require steeper grazing angles in order to circumvent foliage-induced attenuation [1, 2]. So, while polarization mismatch can be significant for different combinations of aspect and grazing angles, one must also weigh the adverse effects of operating at shallower grazing angles when employing a horizontally-polarized slant plane.

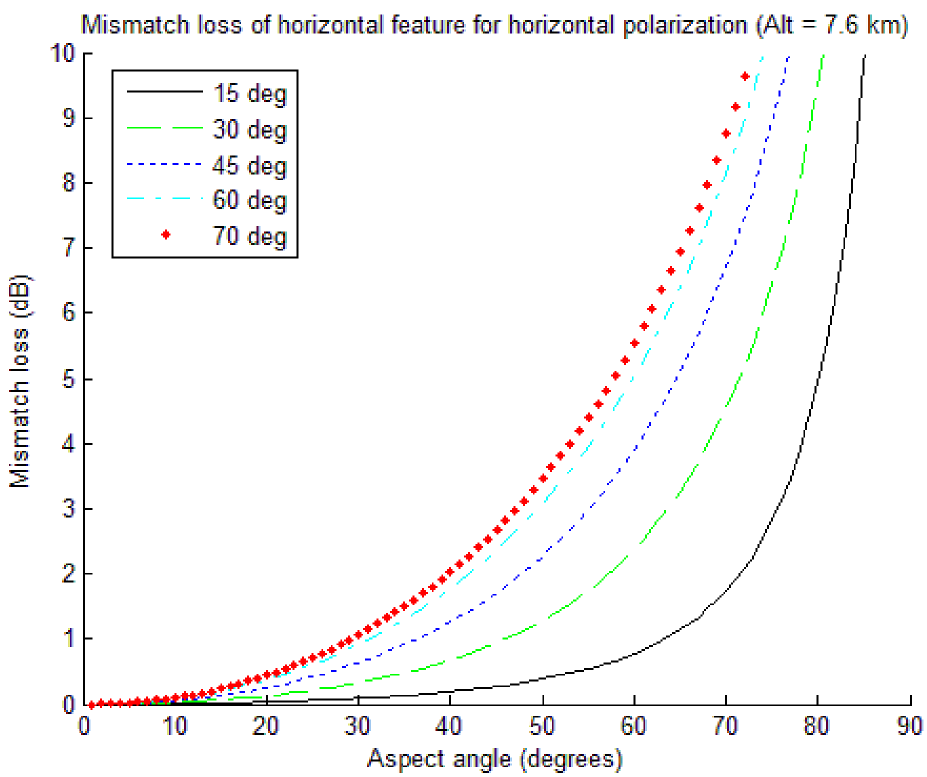


Figure 2. The polarization mismatch loss for the horizontally-polarized slant plane. A fixed altitude of 25,000 ft (7.6 km) was chosen while grazing angles were varied from shallow to steep (15 – 70 deg).

B. Vertically-polarized slant plane

We now investigate the response of the horizontal linear feature when a vertically-polarized radar slant plane is considered. The vertically-polarized component of the target linear feature is determined in a similar manner to that of the horizontally-polarized case. Those steps are repeated here for convenience:

1. The cross-product of $\mathbf{u}_{A\_V}$ and $\mathbf{u}_{LOS}$ is taken to form $\mathbf{u}_N$, which is orthogonal to the vertically-polarized slant plane and is formed at the center of the target
2. The dot-product of $\mathbf{u}_N$ and $\mathbf{u}_{F\_H}$ quantifies the amount of radar return from the linear feature that is <u>not</u> contained in the horizontally-polarized slant plane

The unit vector orthogonal to the vertically-polarized slant plane is derived from the cross-product of the vertically-polarized antenna vector and the radar LOS vector,

$$\hat{\mathbf{u}}_N = \mathbf{u}_{A\_V} \text{ x } \mathbf{u}_{LOS} = [u_y \cos\theta\, i - (u_h \sin\theta + u_x \cos\theta)\, j + u_y \sin\theta\, k] / [u_y^2 + (u_h \sin\theta + u_x \cos\theta)^2]^{1/2},$$

$$= [u_x \tan\psi_a \cos\theta\, i - (u_h \sin\theta + u_x \cos\theta)\, \mathrm{j} + u_x \tan\psi_a \sin\theta\, k] / [(u_x \tan\psi_a)^2 + (u_h \sin\theta + u_x \cos\theta)^2]^{1/2}. \quad (7)$$

Thus, if the dot-product of $\mathbf{u}_N$ and $\mathbf{u}_{F\_H}$ is zero then the return from the linear feature will be entirely contained within the vertically-polarized slant plane. This case results when $\psi_a = 90$ degrees. Conversely, if the dot-product is one then none of the return will be contained within the vertically-polarized slant plane. This is illustrated in Figure 1(b) where the vector orthogonal to the vertically-polarized slant plane is parallel to the Y-axis in the ground plane, while an arbitrary aspect angle adds perspective to the model. As evidenced, the cross-product between the radar LOS vector and the orthogonal vector results in a co-polarization vector that is orthogonal to the radar LOS vector.

To verify this, the dot-product magnitude of the vector normal to the vertically-polarized slant plane and linear feature unit vectors is calculated as,

$$N_{X\_V} = |\hat{\mathbf{u}}_N \bullet \hat{\mathbf{u}}_{F\_H}|,$$

$$= |[-u_x \tan\psi_a \cos\theta \sin\psi_a - (u_h \sin\theta + u_x \cos\theta) \cos\psi_a] / [(u_x \tan\psi_a)^2 + (u_h \sin\theta + u_x \cos\theta)^2]^{1/2}|,$$

$$= |[(-u_x \cos\theta / \cos\psi_a) - u_h \sin\theta \cos\psi_a] / [(u_x \tan\psi_a)^2 + (u_h \sin\theta + u_x \cos\theta)^2]^{1/2}|,$$

$$= |[(-u_x / u_h) \cos\theta - \sin\theta (\cos\psi_a)^2] / [(u_x / u_h)^2 (\sin\psi_a)^2 + (\sin\theta + (u_x / u_h) \cos\theta)^2 (\cos\psi_a)^2]^{1/2}|. \quad (8)$$

Sample calculations verified that $(N_{X\_V})^2 + (N_{Co\_V})^2 = 1$ where $N_{Co\_V} = |\hat{\mathbf{u}}_{N\_Co} \bullet \hat{\mathbf{u}}_{F\_H}| = |[-u_x u_h \sin\psi_a + u_y u_h \cos\psi_a] / [(u_x u_h \sin\psi_a)^2 + (u_y u_h \cos\psi_a)^2]^{1/2}|$. From here, the polarization mismatch loss in the vertical plane is calculated as,

$$L_V = 10 \log_{10} (1 - N_{X\_V})^2. \quad (9)$$

Figure 3 plots the polarization mismatch loss for vertical polarization when various aspect and grazing angles are considered. In our analysis, the altitude was held constant at 25,000 ft (7.6 km) and an antenna tilt angle of 35 degrees was assumed. Both parameters are fairly typical for airborne radar. It can be seen from the figure that the loss increases proportional with decreases in both aspect and grazing angles. Therefore, if one wanted to minimize the polarization mismatch loss for a vertically-polarized radar slant plane, they would essentially do the opposite of what is required in the horizontally-polarized case. Therefore, steeper grazing angles and large aspect angles would yield the best results for the vertically-polarized case. It's important to keep in mind that certain radar applications require shallower grazing angles in order to circumvent clutter backscatter [1, 2]. So, while polarization mismatch can be significant for different combinations of aspect and grazing angles, one must also weigh the adverse effects of operating at steeper grazing angles when employing a vertically-polarized slant plane.

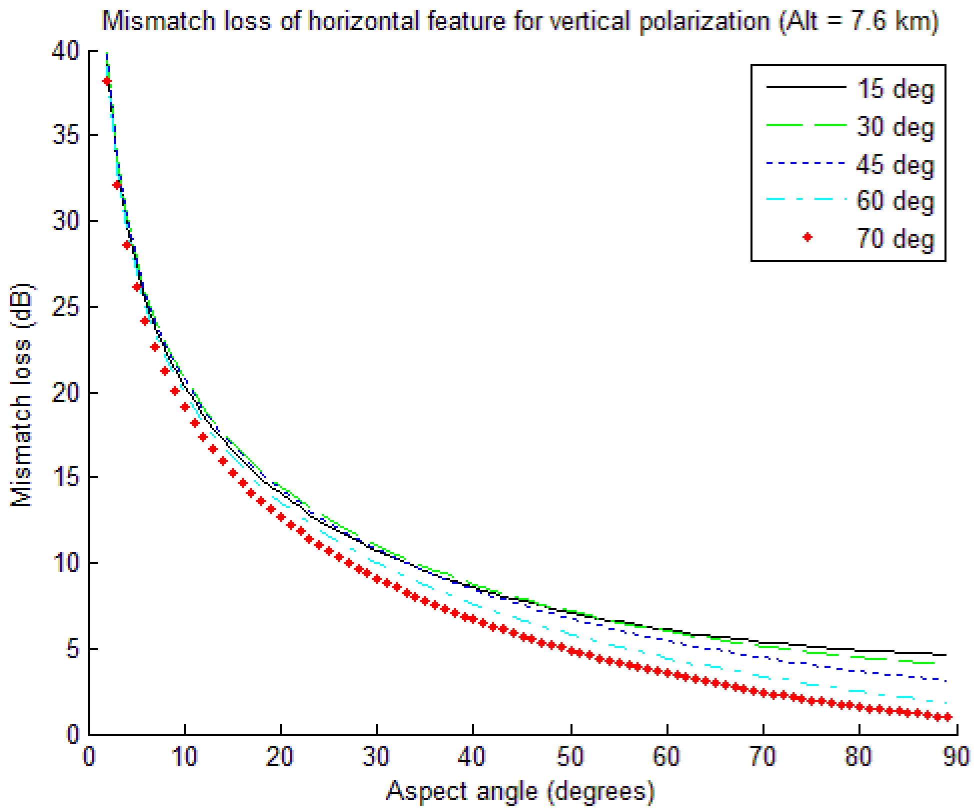


Figure 3. The polarization mismatch loss for the vertically-polarized slant plane. A fixed altitude of 25,000 ft (7.6 km) was chosen while grazing angles were varied from shallow to steep (15 – 70 deg). The antenna tilt angle (θ) is 35 degrees.

IV. CONCLUSIONS

In this paper, a preliminary analysis of the polarization mismatch loss for horizontal linear features was presented. It was shown that when considering a horizontally-polarized slant plane, shallower grazing angles and smaller aspect angles to target would minimize polarization mismatch loss. Conversely, when considering a vertically-polarized slant plane, we observed steeper grazing angles and larger aspect angles minimize polarization mismatch loss. Observations were made on how one might be inclined to compensate for the polarization mismatch loss without considering the severity of foliage-induced attenuation or terrain backscatter. It's important to remember that while polarization mismatch can be significant for different combinations of aspect and grazing angles, one must also weigh the adverse effects of using certain grazing angles for a given terrain-type.

Future work will incorporate measured data from a controlled test environment using US Army airborne radar. A select portion of the experiment will focus on quantifying the aperture integration loss as a function of the horizontal linear feature and various grazing/aspect angles. The findings from both experiments will help identify the total expected loss when different polarizations are used for horizontal linear feature detection.

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